An innovative approach for high-performance road pavement monitoring using black box

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ORIGINAL PAPER

An innovative approach for high-performance road pavement monitoring using black box

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Abstract
One of the criteria adopted by the Word Bank with the aim of defining the economic level of a country is represented by the condition of the road pavements. To ensure adequate road pavement quality, road authorities should be continuously monitoring and repair the detected anomalies. To fast solve problems associated with poor quality of road surface such as comfort or safety, the presence of distress must be detected quickly. The high-performance pavement distress detection, such as those base on the image processing or on the laser scanning, is very expensive and does not allow to the road administration to conduct the appropriate monitoring campaigns. To solve these problems, the paper describes the pave box methodology, an innovative and immediately operational distress detection approach based on the exploitation of data collected by the black boxes located inside the vehicles that routinely pass on the road network. Data processing and the algorithms used in the post-processing evaluation of the vertical acceleration were compared with existing visual surveys procedures such as PCI. Two different indices have been proposed to detect and classify both the local damages and the global condition of the entire road. Pave box provides a robust evaluation of the pavement condition that allows to detect all the severe distress and not less than 70% of the minor damages on the pavement surface. The proposal is characterized by low time and cost consumption and it represents an effective tool for road authorities.

Keywords Road pavement condition · Vertical accelerations · Distress severity index · Distress detection · Road pavements screening · Pavement damage

1 Introduction and background

The importance of road and its efficiency for society could be compared to the importance of oxygen for humans.

The road pavements condition (RPC) represents an important aspect for the development of a country; it shows its economic level and has been adopted by the World Bank as a classification criterion explaining that "the density of paved roads in good conditions vary from 40 km/million inhabitants in low-income countries to 470 in middle-income and 8550 in high-income countries", therefore to maintain an acceptable level of efficiency for the entire road network and to adopt an effective road pavements maintenance program is one of the current challenges for the road authorities (RAs) [1].

Population growth and the expansion of cities have consequently been accompanied by an increase in the volume and weight of traffic, which directly accelerated the damage of the transport infrastructure. The effect of climate change [2], the poor quality of materials used and even the shortcomings in the road design represent further causes of this phenomenon. Overall, the effect of these problems if combined with the road age causes the presence of different type of anomalies on the road surface (such as potholes, cracks, rutting etc). For all types of road context (urban, suburban and highway) all over the world.

Every day, the media bombard us with news say that deficient roadway conditions are a substantially more lethal factor than drunk driving, speeding or non-use of safety

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belts. However, statistics relating to this type of accident are inconsistent due to the large difference recorded in the consequences of the accident, because the effects of the bad road condition can vary from simple vehicle damage to the fatal accident. Conversely, according to the Italian data referred to 2019, 1349 accidents with deaths and serious injuries occurred due to the road surface damage. However, no information is reported relative to the crashes characterized by minor consequences or affected only by vehicle damage [3].

To overcome the inconsistence of the accident data, the Tuscany region published the results obtained in the 3rd statistical survey on road safety conducted by the Regional Road Safety Monitoring Centre (CMRSS). The analysis highlighted that the presence of potholes and other road pavement distress are perceived as the most dangerous element for the mopeds and/or motorcycle drivers (41.6%). The same opinion is also highlighted for 32.8% of the drivers of four-wheel vehicles (car, minicar, van, truck/truck, coach). Furthermore, the comparison with the previous survey, conducted in 2016, highlights the great weight assigned to the road pavement conditions as a risk factor, which doubled in 2018 [4].

To optimize the road pavement management and to ensure the efficiency for mobility of all road users, the pavement management system (PMS) is an effective tool for road authorities. The PMS represent a planning tool that assists RAs in the decision-making process to efficiently maintain the road network in a timely and economical way, as well as to guarantee comfort and safety for all users [5–7] Therefore, to be effective, it requires the availability of road pavement distress data and the possibility of data updating and maintenance.

A traditional approach to the road pavement maintenance and repair involves total or partial replacement of the pavement when significant structural/functional damage has occurred: this approach causes a deepest intervention (and certainly more expensive, as well as more restrictive and/or dangerous for traffic safety) on road pavements, which can cause unsafe conditions for road users before the restoration works, as sufficiently documented in the technical literature [5, 8, 9].

A proactive approach, instead, is oriented towards the conservation of the pavement, trying to create a system relatively less invasive and small-scale repairs on the roads, before the structural damages occur, thus limiting the need for a deeper pavement rehabilitation. Compared to the traditional approach, it will result in long-term savings, reduced traffic congestion, as well as a lower reduction in safety conditions [5, 10].

There are several tools that allow synthesizing the existing road pavement condition, to define the priority intervention order, including prediction of performance and economic analysis. On the basis of the tool adopted, specific input data are necessary, which are characterised by different accuracy and precision levels, and are acquired by different techniques, which contributes to determining the global performance and cost of a PMS [11]. According to the literature review, there are several of the pavement condition indices which are obtained and used to in representing a global or a peculiar aspect of the road pavement. Two of the most used are the Pavement Condition Index (PCI) and International Roughness Index (IRI). The first index was developed to provide a measure of pavement integrity and surface operational condition, while the second one is a standardized roughness measurement, which provides a ride quality classification in term of longitudinal profile, travelled by a wheel path. However, there are several other pavement condition indices, such as PSR or PSI, capable to offer an evaluation of the serviceability and riding qualities of the pavement. Each index is characterized by different measurement and interpretation and can be selected by the RAs as a function of the monitoring procedure adopted.

The IRI index was the one most in tune with acceleration than PCI or PSR. However, the literature has shown that IRI can be poorly correlated to the pavement ride quality in urban areas because speed is one of the most important parameters that affect user comfort [12]. Loprencipe et al. evaluated the use of IRI index for the road unevenness in relation to the road users' comfort, confirming the results obtained by Ahlin et al. that indicated that sometimes IRI can lead to incorrect and not accurate results because in its calculation the contribution provided by some frequencies is underestimated or even not considered. Thus, it can happen that two pavements profiles having the same IRI value can induced completely different acceleration levels [13].

Regardless of the tool adopted, the data collection and analysis phases are the first and the main step to able to implement an appropriate proactive approach [14], to provide the pavement distress labelling and quantification in term of type, severity, and extension.

The pavement conditions can be assessed both by low- or high-performance methodologies; while the former is laborious, time consuming and prone to the subjectivity of inspectors and exposes them to dangerous working conditions, the second one offers an automated or semi-automated detection solution, which minimizes subjectivity, improves productivity, but currently involves the high implementation costs [5–7, 14, 15]. Unfortunately, a global delay in the diffusion of high performance monitoring methodologies emerges due to disadvantages represented by costs and data processing complex operation on the entire road network. At the same time, road authorities are aware that the delay in applying an appropriate PMS leads a more rapid deterioration of a road pavement performance and consequently the relative economic loss [14]. This consideration has increased the interest both of RAs and researchers in the development of high performance procedures for assessing road pavement conditions.

Over the past decade, many studies have focused on detecting road pavement distress, using different technological solutions both for data collection and for their evaluation, to speed up maintenance and repair activities. In recent years, various systems and procedures have been implemented, focused on improving the detection technique, especially to overcome the limits of manual detection [10, 16], increase operational safety and improve the cost–benefit ratio [17]. For example, tools based on artificial vision, shapes segmentation and evaluation of pavement texture have been implemented [17, 18], as well as more recent and elaborate methods based on stereo sensors and on artificial vision and image processing algorithms [6, 7, 19–24]. These methods are based on expensive sensors/devices, time consuming processes and/or common problems related to lighting, occlusions and on the aspect of the anomalies that do not have a prototypical appearance, limiting their accessibility and use.

These reasons, in the last 15 years, have led several researchers to evaluate and implement alternative tools and methods based on cheaper and more widespread technologies, to address this type of problem.

Several procedures have been developed and successfully employed using a vibration-based approach under which road surface anomalies are detected from the rate of moving vehicles' vibrations captured by motion sensors (e.g., accelerometers or gyroscopes). Theoretically, in fact, a vehicle, when passing over any road surface anomaly (such as a pothole, crack, manhole, or expansion joint, etc.) will vibrate more than when passing over smooth road surfaces [25].

Many of these studies have been performed to improve the accuracy of vibration-based detection by combining other sensor data, such as GPS [26–28] and designing advanced algorithms. Ngwangwa et al. [29], for instance, have developed an algorithm based on artificial neural network that reconstructs road surface profiles from measured vehicle accelerations and, at a later time, testing its effectiveness at a later time through experimental applications [30]. Other authors, instead, proposed an optimisation algorithm, based on cross entropy theory, to predict road irregularities from vehicle accelerations [31, 32]. These approaches, factual, require the use of tool equipped with accelerometers (mono- or tri-axial), gyroscopes and GPS antenna (specifically, used both for measuring the speed of travel and for the location of the section analysed).

These sensors are now present in all basic configurations of smartphone mobile phones and, therefore, over the last few year smartphone-based sensing has emerged as an attractive alternative technique for detecting road surface anomalies, given its detection, geo-referencing and networking capabilities [25, 33, 34].

Several efforts have been made in this research field and numerous studies can be found on it. Some of these have focused on the development of algorithms for detecting individual road anomalies (especially, potholes) starting from the measurement of vertical accelerations [35–42]. Others, on the other hand, have undertaken to create algorithms capable of converting vertical acceleration measurements to pavement performance indicators. Specifically, they have studied the smartphone ability in evaluating the pavement ride quality with respect to the International Roughness Index (IRI), obtaining satisfactory results in terms of comparing calculated IRI and estimated [43–49].

These systems are particularly useful and valid given its detection, geo-referencing and networking capabilities, as well as by virtue of using an approach based on the concept of crowdsourcing and "participatory sensing" in which the data recorded by all users on the road network are collected, shared and added as a layer to the existing navigation, such as Waze, Google Maps, etc., that use real-time traffic information [50]. However, this research topic is quite challenging and there are still some challenges to be faced. Among these, the development of standardized methods for the detection, classification, and characterization of road anomalies certainly emerges [25, 33, 51]. Although the type of approach to be applied for road anomalies detection is already defined, the practical application of the procedures cannot have immediate application due to restricted availability of the reported algorithms for analysis and classifying the information recorded. In addition, many of these using threshold-based approaches and how the threshold was set still remains unclear [25]; finally, the described methodology approaching to the road pavement condition detection by accelerometers, black boxes or smartphone was often combined with the most modern technologies like those based on the image processing (such as radar, lidar, ARAN ® or similar). Therefore, the cost-effectiveness of the procedure fails when included in a very high technology system [7, 15, 24].

In conclusion, a road pavement management system should guide RAs in a proactive process, aimed at guaranteeing safety and comfort to all road users through the continuous process of inspection, detection and mitigation of road pavement distresses. This consideration highlights the importance of using specific tools to identify road pavement conditions. Indeed, a crucial point for road authorities is the selection of the appropriate devices to be used for the detection of road damages according to the cost–benefits ratio. Encouraging, therefore, the adoption of low-cost detection technological solutions allows to overcome the lack of information and, high-precision tools, can facilitate the management of road pavement, even for minor RAs. Therefore, the study aims to present a low-cost alternative technological solution that allows monitoring road pavement distress on the entire road network, by the detection carried out with floating car data of vehicles equipped with insurance black box. The black boxes allow greater reliability and uniformity in acceleration recording if compared to the smartphones, because the device requires some attention in its installation inside the car, and it remains in the same place of the vehicle for all cars' passages. Vice versa the smartphone could wear both by the drivers or by the passengers affecting the precision of its measurements.

2 Research objectives

The review of the main existing research on the topic, reported in the previous section, highlights that to take a step forward in monitoring the condition of the road surface, it is important to provide RAs with a tool that allows them to obtain a reliable screening of the road pavement condition of the entire road network, promoting tool characterized by high performances, low cost, user friendly and readable for the operators involved.

In this context, the authors propose *Pave Box* methodology: an approach based on the processing of the vertical accelerations and GPSs data recorded by the black boxes located inside the vehicles that routinely pass on the road network.

The objective of this research is to define an operating procedure that aims to carry out a network screening. The monitoring procedure is focused on identifying the most damaged road pavement sections by exploiting knowledge on the "floating car data" deriving from the black boxes inside the vehicles. This paper introduces preliminary experimental results to explore the possibility of using vibration data (vertical acceleration) recorded by black boxes, to detect and to classify the road pavement surface distresses.

Unlike the approaches mentioned in the previous section, this study does not intend to obtain an indirect estimate of one of the main the pavement condition indices or to detect only individual road anomalies, but rather to evaluate the possibility of using the procedure developed which aims to identify a limited number of severity classes from which obtain an immediate screening of the state of conservation of the road network pavement also at a global level and not only punctually (i.e., by locating only the single anomaly).

The low cost of the system is not the only advantage. Indeed, if many vehicles equipped with similar systems move through the roads, the "scanning" of the network could be done in real time; therefore, information on the road pavement condition, could be updated by the ICT system that manages data storage and adds them as a layer to the existing navigation system such as GIS or Waze, Google Maps, etc. Therefore, the outcomes of this research could potentially eliminate or reduce the time for collecting, reviewing and processing road pavement distress.

The procedure proposed may provide an initial and inexpensive assessment of the condition of the road pavement surface. The assessment could either be used directly for making maintenance decisions or could be utilized as input into more comprehensive road maintenance management systems.

The acceleration data set, preliminarily validated by statistical comparison between the accelerations registered in the same location (such as in the same pothole), was used to define both detection and classification algorithms, as well as to localize the anomaly and its severity levels on the maps.

3 Methodology

3.1 Apparatus

The black box used for the evaluation of the road pavement condition (RPC) is a very simple device equipped with:

- one inertial accelerometer working in the three directions *X*, *Y* and *Z*;
- one tri-axial gyroscope able to record the rolling, pitching and yawing movements of the car, and
- one GPS device.

All data are collected in the three directions. No requirements are initially defined about the technical performances of the black boxes used in the process. However, all the tests performed in this research were conducted with black boxes characterized by a sampling time of 0.001 s (100 Hz) according to the most valuable research considered in the literature review [37, 38, 49]. This precision in data recording allows detecting all road pavement anomalies greater than 2 cm long, according to the posted speed limit in Italian urban context, ranging from 30 km/h to 50 km/h. The more precise tool allows for better detection of distress [28]. Instead, the use of the black boxes with sampling time less than 0.05 s (20 Hz) are not recommended because they do not allow to detect anomalies smaller than 10 cm long, and, therefore, they are not useful for the main objective.

The devices used in the research allow recording a maximum acceleration value for each direction equal to 16 g.

The black box used in the experiment has been previously calibrated and does not require any installation procedure. It is very important that it is fixed on a floorboard, firmly connected to the vehicle. Before starting the survey, but after starting the car engine, drivers turn it on. After 5 s (time needed to stabilize the GPS connection), the test can begin. To assign each detected distress in the correct location (homogeneous section), the GPS connection must be preliminary verified. When the precision indicated by

Fig. 1 Road sections selected during the development of detection algorithms

the GPS device is less than 5 m, the condition should be reported as an accuracy warning; however, this "failure" does not affect the evaluation of the local and global indices until it exceeds 10 m. To verify the accuracy of the GPS signal, a calibration process according to that proposed by Eriksson [28] is suggested.

3.2 Road segment tested

Three different road sections located in the Municipality of Prato have been selected with the aim of optimizing the data recording process and developing of algorithms for the detecting road surface distress. In Fig. 1, the three selected road sections are shown.

All selected road segments are located in an urban context. In all cases, the carriageway is composed by two lanes, one per direction. The lane width ranges between 3.0 and 3.5 m. The three streets are located in different part of the Municipality of Prato and they are characterized by heterogeneous traffic that includes both light and heavy vehicles, as well as mopeds and motorcycles. Specifically:

- the road section of via del Maceratoio is about 290 m long. The street was selected because it offers a good road surface condition thanks to the recent re-pavement intervention carried out no less than one month before the tests;
- the road section of via Alessandro Scarlatti is about 290 m long. The street was selected because it offers a road surface characterized by the presence of potholes, patches and alligator cracking;
- the road section of via Olinto Nesi is about 330 m long. This section was also selected due to the presence of big potholes and fatigue cracking on the road pavement.

To test the reliability of the proposed monitoring process, a last 200-m-long road section was selected. Via Toscana (Fig. 2), similarly to the other streets is characterized by two lanes, one for each direction. Each lane is about 3.25 m width. The road is located near an industrial area and the traffic is intense and characterized by heavy vehicle. As can be seen from the image, the road surface is damaged.

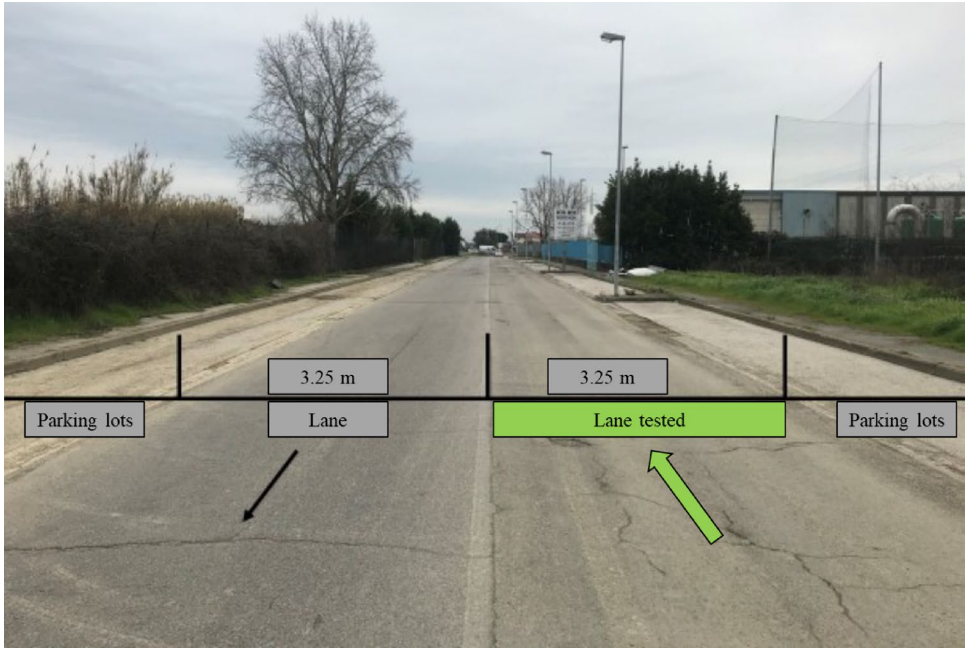


Fig. 2 Road segment selected for final test

3.3 Procedure

The measurement was conducted according to the following procedure:

- *Step 1—segmentation process*: each street evaluated was divided into different homogeneous section about 100 m long. Where the road stretch was longer or less than 100 m, the final section will have a different length. All sections will have to have a total length not less than 50 m and not more than 150 m.
- *Step 2—road assessment*: each street was subject to multiple passage of cars with speed according to both the posted speed limit in urban areas and the road condition during the passages (min. 30 km/h, max 50 km/h). The cars were equipped with black boxes fixed on the floorboard, between the pedals and the gearbox, but in a safety position. This represents the best position to minimally affected the acceleration value recorded due to the effects on the vehicle related to the curvilinear trajectories as well centrifugal or/and centripetal acceleration. It is also the easiest position to switch the black box on and off during testing. The vertical accelerations, time and GPS positions of each passage were recorded.
- *Step 3—data post-processing*: the data recorded were post-processing in terms of vertical acceleration (average and peak values and descriptive statistical).
- *Step 4—distress detection algorithms definition*: two detection algorithms will be proposed to define two different indices; the first referred to a local anomalies and the second one referred to a global description of the road pavement conditions. The anomaly threshold was defined with reference to the traditional PCI process [52].
- *Step 5—graphic publication of the result*: all useful and consistent information capable of describing the road pavement conditions (presence/absence of distress and its severity level) were localized by means of GPS coordinates in GIS map.

All tests were carried out using the same vehicle, a Seat Leon 5F 1.2 TSI. The use a common sedan made it possible to adapt the operational procedure to all types of cars according to the research goals. Before the monitoring process, each tire was verified and adjusted to the recommended tire pressure (2.4 bar).

3.4 Data collection and analysis

According to the purpose of this study, the data analysis resulting from the in situ evaluation of the road pavement condition focused on the following measurements:

- time;
- vertical acceleration;
- GPS position of the vertical acceleration values recorded;
- speed of the instrumented vehicle.

The measurement of the GPS coordinates and vertical accelerations constitute the dataset to be processed for both the identification and classification of the pavement surface damage severity. Instead, the speed measurement was performed to control the consistency of the survey.

Two different indices were proposed:

1) *Local Pave Box index (LPBi);*

The LPBi is based on the analysis of the vertical acceleration measured along the 100 m long homogeneous segment. The LPBi value was processed with reference to the peak value of the moving variance of the vertical acceleration. Mean and standard deviation were evaluated to describe the dispersion of the peak value recorded in different measurement of the same anomaly.

2) *Gobal Pave Box index (GPBi);*

As proposed in the traditional pavement monitoring methods [52], in this research, a global distress index (GPBi) was proposed. The index describes a global evaluation of the entire road segment damage; it is useful to screen and compare different road segment or entire road network areas characterized by different pavement condition. The GPBi is based on the evaluation of the line integral of the moving variance curve estimated from the row vertical acceleration data measured. Mean and standard deviation were assessed to describe the dispersion of the value of different measurement.

3.4.1 Moving variance evaluation—local pave box index

The analysis of data resulting from the in situ tests focused on the post-processing of the vertical acceleration recorded by all the black box measurements. All data collected refer to the three road sections analysed. The measurements were conducted in redundant number with the aim of evaluating the dispersion of the response provided by each evaluated indices, as previously specified.

In this study, overall 30 measurements of the a_v were carried out in the sample homogeneous segment (10 for each street selected) and processed in this study. Each signal was processed and clean from the noise by means of the moving variance[1] of the vertical acceleration evaluated over a sliding window of 0.2 s length, across the central range value; with the aim of clean the row signal, but without "delete" the effect of the anomalies greater than 10 m according to the GPS accuracy in distress location. The variance was mainly used because it is a descriptive statistical index, which, by definition, assumes only positive values (unlike the recorded a_v) and, at the same time, it represents the dispersion of the variable studied over time and space.

With a sampling frequency of 100 Hz, each range includes 20 sequential measurements. The moving variance $\widehat{\sigma^2}$ is estimated by means of the Eq. (1).

[1] The moving average is the most common filter in DSP, mainly because it is the easiest digital filter to understand and use. Despite its simplicity, the moving average filter is optimized for a common task: reducing random noise while retaining a sharp step response. This makes it the premier filter for time domain encoded signals.

$$\widehat{\sigma^2} = \frac{\sum_{i=1}^{n} \left(a_{v,i} - \overline{a_v}\right)^2}{n} \tag{1}$$

where $a_{v,i}$ represents the ith vertical acceleration value; $\overline{a_v}$ represents the moving mean across a range of 20 values (0.2 s) centred in x_i, as defined in the Eq. (2); n is equal to the number of sampling in the considered range, equal to 20.

$$\overline{a_v} = \frac{\sum_{i-9}^{i+10} a_v}{n = 20} \tag{2}$$

The variance represents a numerical value used to indicate how widely individual measurement vary from the population mean where it is included. One road pavement in good condition (without distress) generates a signal whose variance assumes contained (not far from zero) values around its mean value represented, in this case, by the gravity acceleration (9.81 m/s^2). Instead, the variance of damage pavement is characterized by high values in all time gaps where distresses are located.

An example of pothole and alligator cracking accelerograms are represented in Fig. 3. In Fig. 4a, b, the moving variance corresponding to the Fig. 3a, b accelerograms are shown, respectively. It can be seen that the moving variance both reduces random noises and normalize the vertical acceleration values across the time according to the next steps.

The data processing allows (see green graph in Fig. 4) to observe that both example sections showed a regular road surface for the first ten seconds of surveys (approximately 100 m long). Still, in Fig. 4a after 12 s, the value of the moving variance (0.2 s) grows until it reaches a peak, which represents a big pothole on the road surface (approximately 5 cm deep). In Fig. 4b something similar happens. A peak representing an alligator cracking distress is shown.

To define the severity levels of each single anomaly on the road surface, similar to the severity levels defined in the PCI procedure [52], three severity levels of local distress were defined (low, moderate and high). The correspondence of the severity levels combines the PCI severity levels with the peak value reached on the moving variance curves across the 20 values considered as shown in Fig. 5.

To better describe the LPBi with reference to the number of available measures recorded day after day, it is suggested to evaluate the average values of the peak located in the same place (referred to each survey). Then, the average value obtained day by day will be associated with the standard deviation referred to all available measurement.

3.4.2 Line integral—global pave box index

The second step of the post-processing data was referred to the evaluation of the comprehensive homogeneous

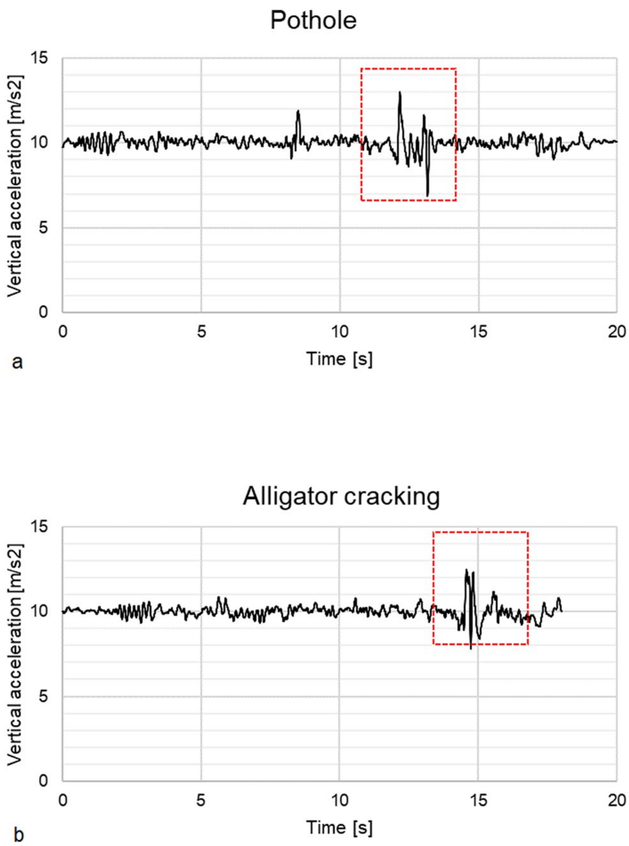


Fig. 3 Accelerograms examples (**a** pothole, **b** alligator cracking)

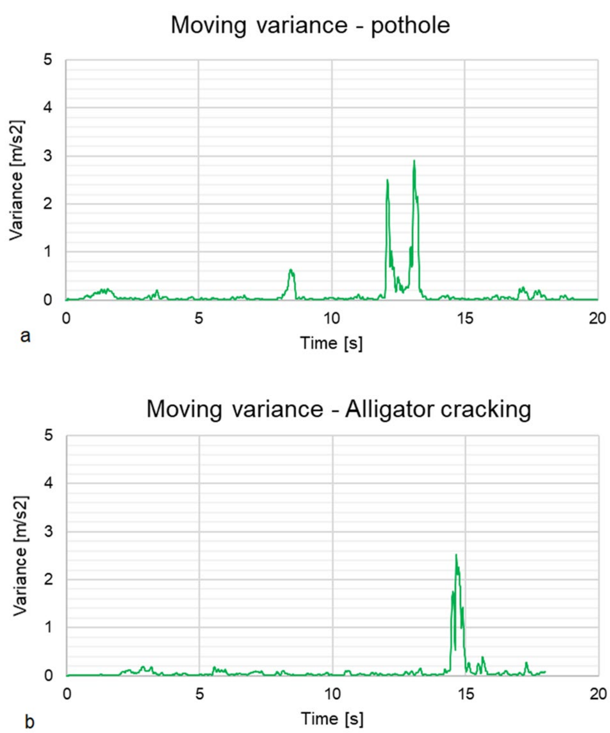


Fig. 4 Moving variance of the example distresses (**a** pothole and **b** alligator cracking)

segment distress (100 m long). The analysis was begun from the moving variance curve obtained from the first step of post-processing data previously described.

The comprehensive evaluation of the segment' severity levels was conducted by an algorithm that

- evaluate the dimension of the area bounded by the moving variance curve (line integral) as represented in Fig. 6. The grey area is proportional to the irregularity (anomalies etc.) on the road surface within the road segment analysed. This process allows to include in the results (GBP index) also the vibrational effect of non-significant distresses, however, on the road surface (irregularity);
- define the GPB index severity levels normalized over a 100 m length.

The GPB index is evaluated by means of the Eq. (3).

$$GPBi = \left(\int_0^L \widehat{\sigma(l)^2} dl\right) \times \frac{100}{L}, \tag{3}$$

where $\widehat{\sigma(l)^2}$ represents the moving variance of the signal measured by black box; L represents the total length of the homogeneous road segment.

According to the evaluation of the LPBi, three different ranges were defined to identify the severity levels of the Global Pave Box index: poor, fair and good (Fig. 7). The thresholds of each level were defined with reference to the PCI severity classification [52]. A special class was defined to indicate all conditions in which road pavement surface urgently needs restoration (need to repair).

The assessment of the GPBi can also be improved measure by measure. Therefore, it is suggested, as for the LPB_i index, to evaluate the average value of the GPB index for each section day by day, and to associate it the relative standard deviation to understand how the data recorded were spread over time.

3.4.3 Threshold definition

To propose a reliable tool to monitor and evaluate the road pavement condition by means of the *pave box* methodology, the ASTM D6433-18 played a fundamental role. As described in the previous paragraph, the proposal for the severity level thresholds was referred to the PCI severity levels definition [52] both for LPB and GPB indices.

With the aim of correlating the PCI severity levels with our thresholds, a large campaign of PCI surveys was carried out on the road sections which were then tested with the new proposed methodology (Pave Box methodology). Specifically, in the PCI survey:

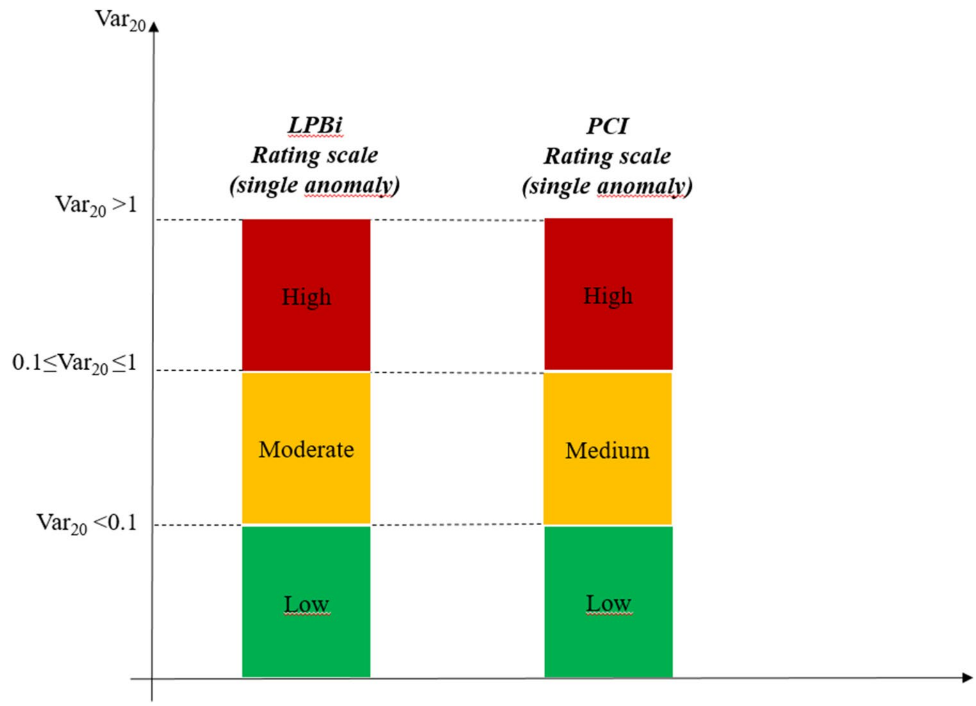


Fig. 5 Severity levels

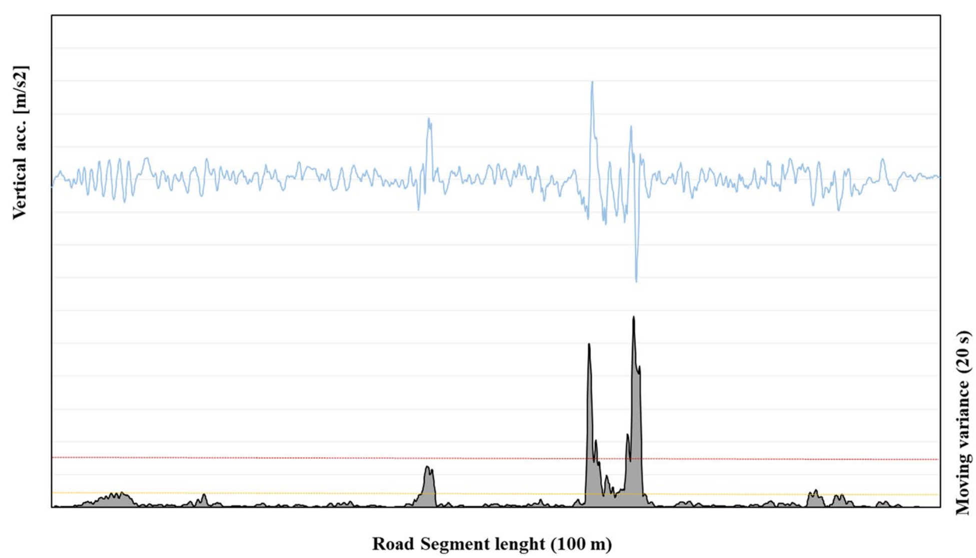
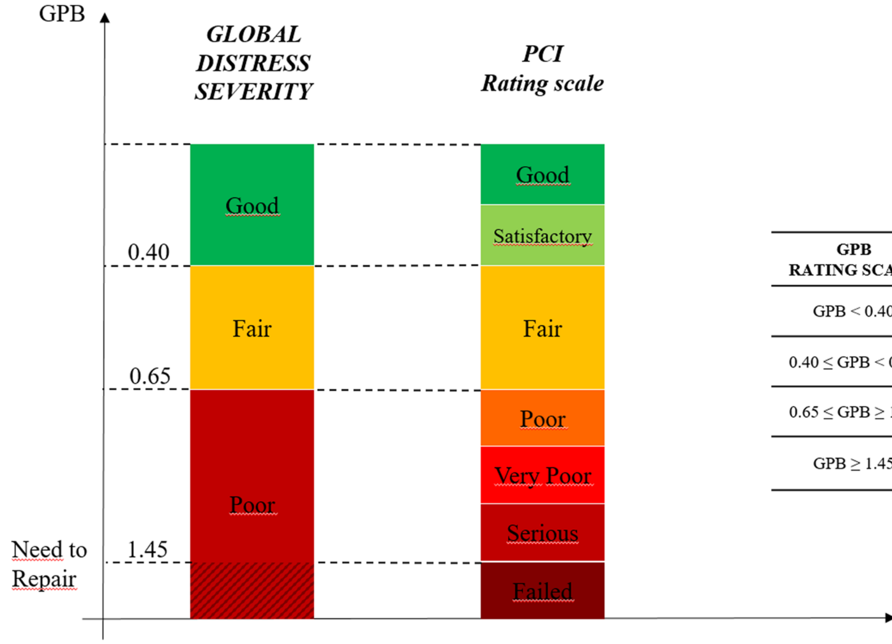


Fig. 6 Evaluation of comprehensive severity levels of road pavement segment

a. each single distress was characterized in terms of severity level defined as indicated in the Appendix of the ASTM standard [52] as shown in Fig. 8;
b. all the sample unit analysed were characterized before by the PCI value than, they were subjected to the pave box monitoring process to define an empirical correlation between the two indices used as shown in Fig. 9.

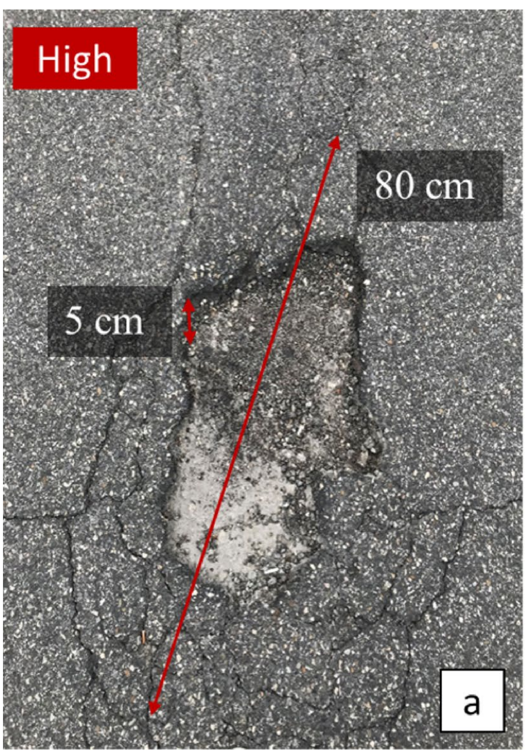
a. To define a simple correspondence between the local damage and LPB index, each anomaly (Fig. 8a) can be analysed by the ASTM Appendix Catalogue (Fig. 8b). After this first classification, the distress was measured in terms of vertical acceleration by black box and, therefore, was characterized in terms of moving variance peak (Fig. 8c). The minimum mean value defined for the different 100 conditions evaluated (high severity) it was taken as the threshold value. The process has been repeated for medium and low severity levels and it is described in detail in [53].

b. To define a simple correspondence between the PCI values of each single sample unit and its global damage index (GPB) the empirical correlation defined in the following graph have been found (Fig. 9). This analysis is currently underway, in fact, an increasing in the dataset



GPB RATING SCALE	SEVERITY LEVELS		PCI RATING SCALE
GPB < 0.40	GOOD		100 - 70
0.40 ≤ GPB < 0.65	FAIR		70 - 55
0.65 ≤ GPB ≥ 1.45	POOR		55 – 25
GPB ≥ 1.45	NEED TO REPAIR		≤ 25

Fig. 7 Global severity levels



b

TABLE X1.1 Levels of Severity for Potholes

Maximum Depth of Pothole	Average Diameter (mm) (in.) 100 to 200 mm (4 to 8 in.)	200 to 450 mm (8 to 18 in.)	450 to 750 mm (18 to 30 in.)
13 to ≤25 mm (½ to 1 in.)	L	L	M
>25 and ≤50 mm (1 to 2 in.)	L	M	H
>50 mm (2 in.)	M	M	H

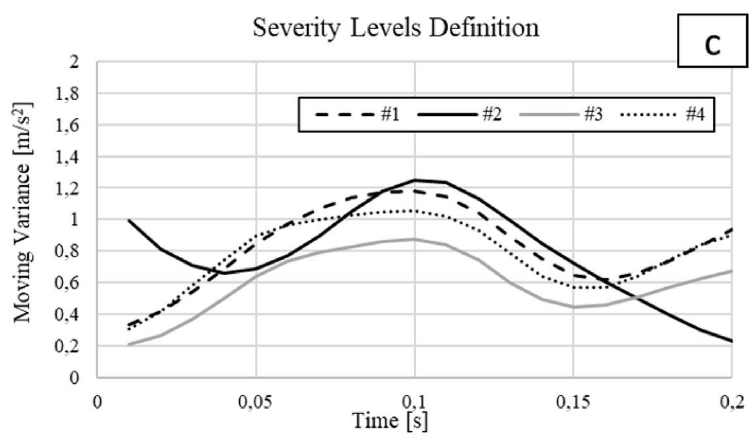


Fig. 8 Defining threshold severity levels [52]

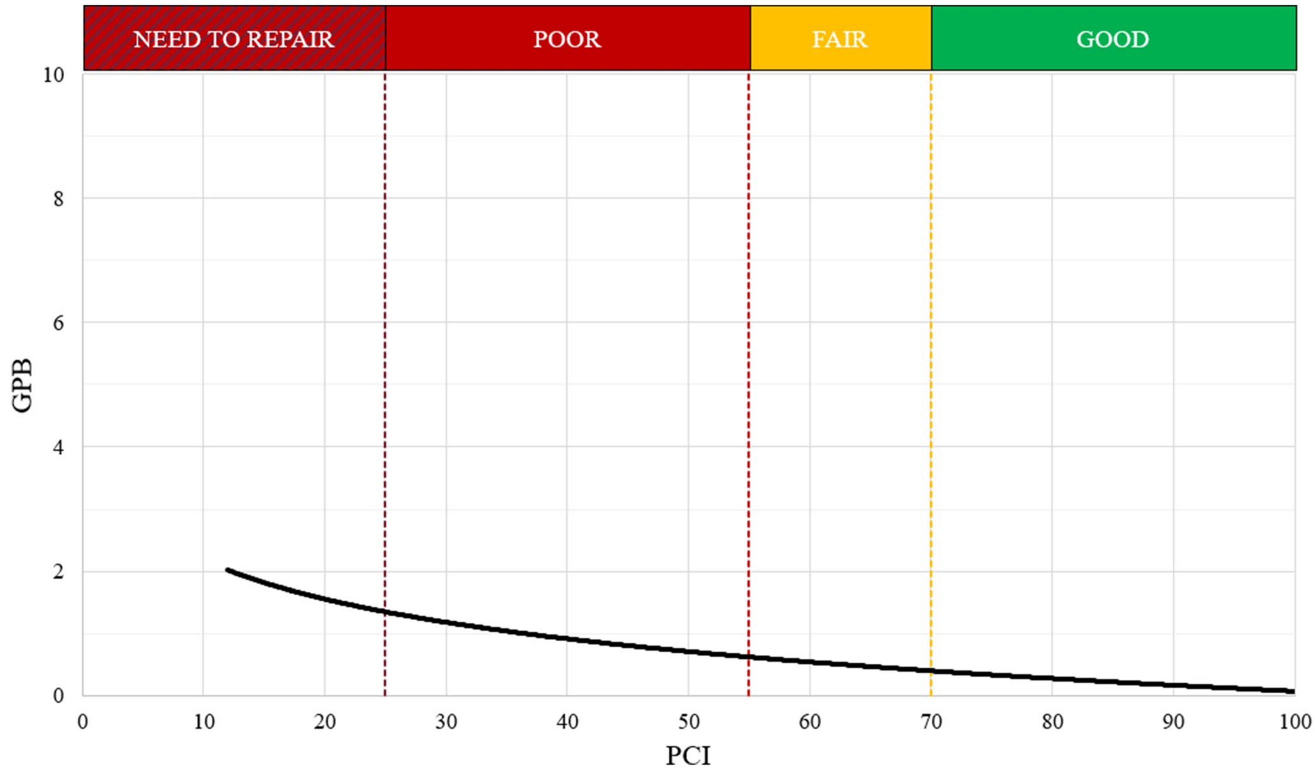


Fig. 9 PCI-GPB empirical correlation

helps to increase the goodness of fit of the mathematical function in Eq. (4) which allows to correlate PCI and DPB indices [53].

$$GPB = -0.922 \times ln(PCI) + 4.3136, \tag{4}$$

where the PCI represents only the values that were used in the definition of the empirical function necessary for the identification of the thresholds.

4 Results and discussion

4.1 Via del Maceratoio

A total of 10 surveys were carried out at 40 km/h. In Fig. 10 the results obtained were plotted. The black curve represents the mean vertical acceleration measured by black box. The grey one represents the moving mean (centered) across 0.2 s with reference to the average value of the raw signal (a_v). The purple curve represents instead the moving variance (VAR20) along the analysed road segment.

The road section within via del Maceratoio was selected in the process to evaluate the effect on the vertical acceleration due to vibration in a recently repaved road, characterized by a regular surface. The analysed VAR20 allows investigating the road pavement condition both in terms of local anomalies and global segment damage.

4.1.1 Local pave box index

The moving variance (purple curve) in Fig. 10 shows a very regular trend. In the first 230 m, no peaks higher than 0.1 m/s^2 were identified. The maximum peak value is 0.042 m/s^2 and occurred approximately 85 m from the origin. The corresponding a_v moving mean is 9.655 m/s^2. In the last 60 m of the road section two local anomalies were identified by the proposed monitoring procedure. In both cases the VAR20 values were higher than 0.1 m/s^2. Table 1 summarized the result obtained in the evaluation of the peaks located at the end of the road segment 290 m long.

The mean values of the two peaks located in the last 60 m of the road segment are 0.197 m/s^2 and 0.194 m/s^2, respectively. None of the 10 VAR20 was characterized by values lower than the threshold defined for the moderate severity level. To verify the accuracy of the LPB index, a manual verification was conducted for all 10 measurements carried out [28]. According to the LPBi there were no anomalies in the first 230 m. There were two small areas (< 0.5 m^2) of

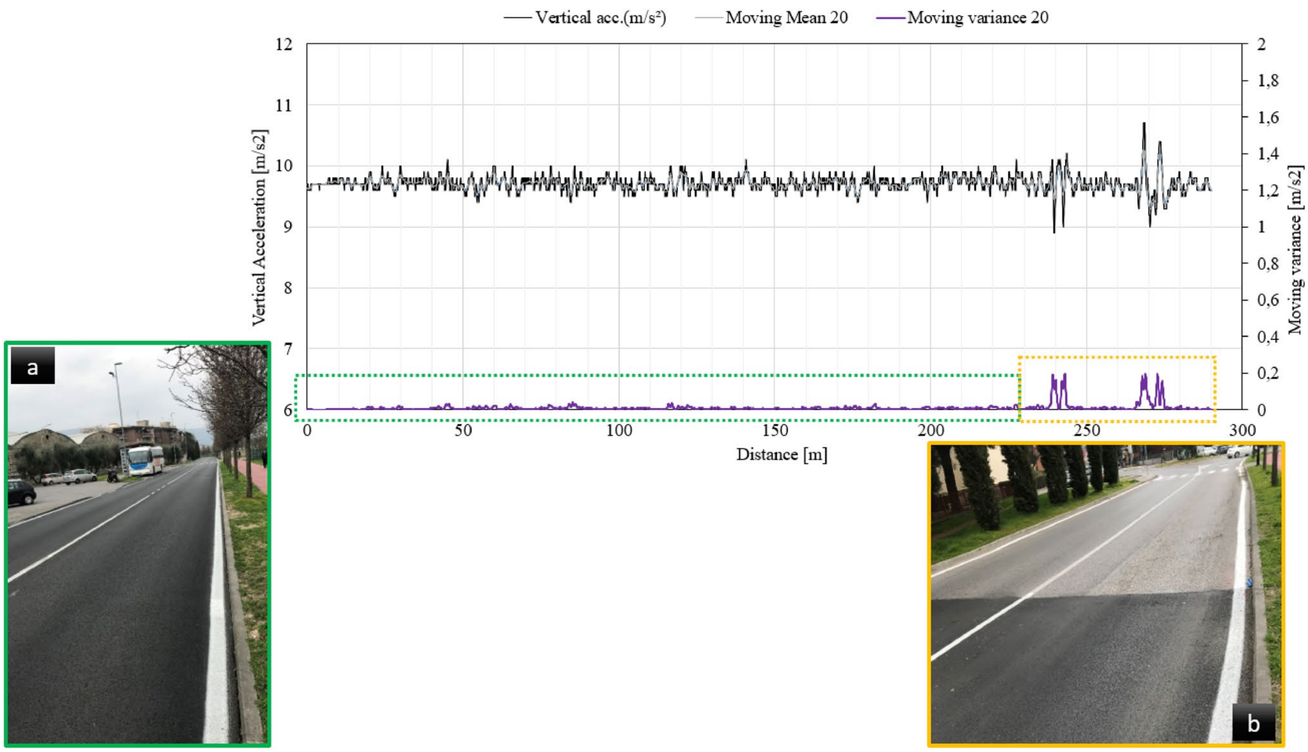


Fig. 10 Via del Maceratoio

Table 1 Local distress index results

Peak ID	Peak value of VAR20 [m/s^2]										LPB [m/s^2]	St. Dev [m/s^2]	Severity levels
1	0.182	0.180	0.203	0.211	0.192	0.187	0.199	0.210	0.197	0.213	0.197	0.0013	Moderate
2	0.183	0.184	0.203	0.209	0.185	0.187	0.191	0.197	0.204	0.195	0.194	0.0008	Moderate

Table 2 Global distress index results

Segment ID	Segment length[a] [m]	a_v mean value [m/s^2]	VAR20 mean value [m/s^2]	GPB	Severity levels
1	100	9.7160	0.0070	0.1005	Good
2	100	9.7053	0.0071	0.1016	Good
3	90	9.7114	0.0207	0.2395	Good

[a]All values in table have been referred to the segment' length

alligator cracking where the monitoring procedure detected two moderate anomalies. (Fig. 10b).

4.1.2 Global pave box index

Table 2 summarized the result obtained in the evaluation of the global distress indices on via Del Maceratoio.

The GPB index represents the average value of the 10 surveys conducted. The values of the GPB shown in Table 2 were very close to 0. Consistently with the purple graph in Fig. 10, the road pavement condition in the first 230–240 m of the road segment was characterized by a good surface. The mean values of the raw vertical acceleration data for each homogeneous segment were 9.7160 m/s^2, 9.7053 m/s^2 and 9.7114 m/s^2, respectively. The mean values of the VAR20 for each homogeneous segment were very close to 0. According to the manual verification conducted to demonstrate the robustness of the monitoring process, the measurement carried out allows a good description of the road surface represented in Fig. 10a and in Fig. 10b. 100% of local anomalies were identified and there were not positive false.

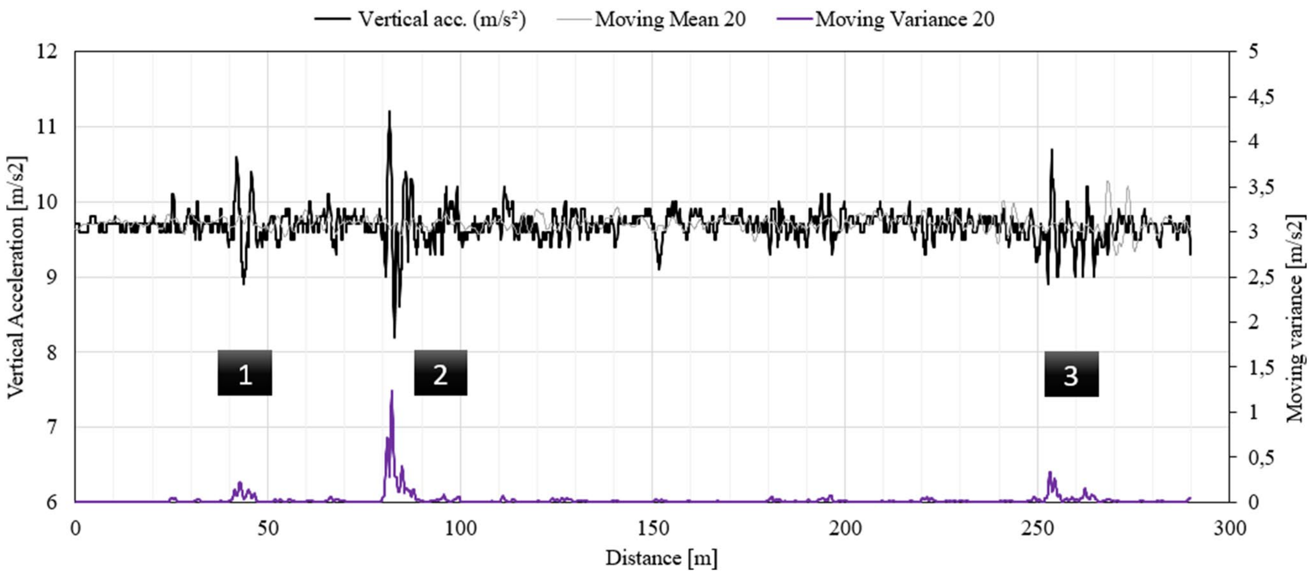


Fig. 11 Via Alessandro Scarlatti

Table 3 Local distress index results

Peak ID	Peak value of VAR20 [m/s^2]										LPB [m/s^2]	St. Dev [m/s^2]	Severity levels
1	0.224	0.202	0.244	0.232	0.232	0.234	0.194	0.252	0.199	0.238	0.225	0.0189	Moderate
2	1.294	1.145	1.274	1.162	1.315	1.163	1.289	1.288	0.142	1.362	1.244	0.0815	High
3	0.301	0.373	0.305	0.368	0.317	0.378	0.376	0.322	0.365	0.309	0.342	0.0330	Moderate

In conclusion, the comparison of the numerical values of the estimated integral (GPB index), for normalized sections over 100 m, with the visual survey carried out on the road pavement, allows to verify the consistence of the proposed monitoring process with reference to a road section characterized by good surface conditions.

4.2 Via Alessandro Scarlatti

A total of 10 surveys were carried out at 40 km/h. Figure 11 represents the result obtained. The black curve represents the mean vertical acceleration measured by black box. The grey one represents the moving mean (centred) across 0.2 s with reference to the mean value of the raw signal (a_v). The purple curve represents instead the moving variance (VAR20) along the analysed 290 m long road section.

The road segment within via Alessandro Scarlatti was selected to evaluate the effect on the vertical acceleration due to the vibration caused by damaged road surface, characterized by the presence of some distresses with different severity levels. The analysed VAR20 allows investigating the road pavement condition both in terms of local anomalies and global segment damage.

4.2.1 Local pave box index

Three different local anomalies were highlighted in the road segment analysed within via Scarlatti. The three peaks were characterized by the VAR20 values summarized in Table 3. Their LPB values were 0.225 m/s^2, 1.244 m/s^2 and 0.342 m/s^2, respectively.

Several other peaks were identified in the moving variance and they were characterized by values less than 0.1 m/s^2. Some of these were characterized by LPB values between 0.05 m/s^2 and 0.1 m/s^2. Not all detections occur in all surveys carried out.

To demonstrate the effectiveness of the proposal, a visual survey was carried out. The three different peaks characterized by moderate and high severity were immediately identified. In Fig. 12 these distresses and their severity levels were represented.

The mean values of the peaks located in the road section ranges from a minimum of 0.225 m/s^2 (anomaly n.1—Fig. 12) to a maximum of 1.244 m/s^2 (anomaly n.3—Fig. 12). The comparison between the visual survey and the proposed automatic detection confirms the robustness of the method to detect the distress characterized by a moderate or

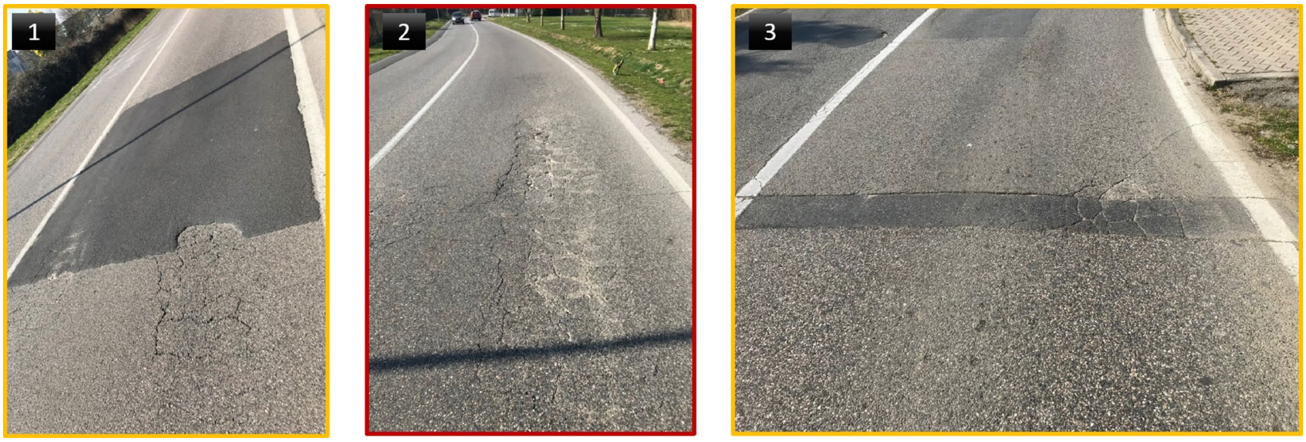


Fig. 12 Anomalies located in via Alessandro Scarlatti

Table 4 Global distress index results

Segment ID	Segment length[a] [m]	a_v mean value [m/s^2]	VAR20 mean value [m/s^2]	GPB	Severity levels
1	100	9.6955	0.0420	0.5431	Fair
2	100	9.6978	0.0112	0.1496	Good
3	90	9.6583	0.0208	0.2181	Good

[a]All the values in the table have been referred to the segment' length

high level of severity. All the passages allow the identification of these three anomalies.

With reference to "minor peaks" (0.05 m/s^2—0.1 m/s^2), according to the procedure implemented by Eriksson et al. [28] and Mednis et al.[37], with the aim of defining false positive/negative only the information contained in more than four findings was considered. The other information was considered false positive (acceleration' noise).

The monitoring procedure proposed allowing to identify 77% of the anomalies, corresponding to the minor peaks. The remaining 23% were confused with the physiological oscillations of vertical acceleration. 30% of the minor peaks identified in the moving variance curve were not related to any relevant anomaly.

4.2.2 Global pave box index

Table 4 summarized the result obtained in the evaluation of the global distress indices on via Alessandro Scarlatti.

The GPB index represents the average value of the ten surveys conducted. The GPB values shown in Table 2 for the homogeneous segments were consistent with the trend of the moving variance curve. The purple curve in Fig. 11 and the evaluation of the LPB also showed the presence on the road surface of high damage within homogeneous segments classified as fair.

According to the manual verification conducted to demonstrate the robustness of the monitoring process, the measurement carried out allows a good description of the road surface represented in Fig. 11a and in Fig. 11b. In conclusion, the comparison of the numerical values of the estimated integral (GPB index), for normalized sections over 100 m, with the visual survey carried out on the road pavement, allowed to verify the consistence of the proposed monitoring process with reference to a road section characterized by fair surface conditions.

As previously described the proposed methodology has not allowed to detect only the 23% of the "minor distresses", but fully detected the "major anomalies" and the sections where they were present.

The combination of the two indices (local and global) was able to describe the real condition of the road surface with good reliability.

4.3 Via Olinto Nesi

A total of ten surveys were carried out at 40 km/h. Figure 13 represents the result obtained. The black curve represents the mean vertical acceleration measured by black box. The grey one represents the moving mean (centred) across 0.2 s with reference to the mean value of the raw signal (a_v). The purple curve represents instead the moving variance (VAR20) along the analysed road segment.

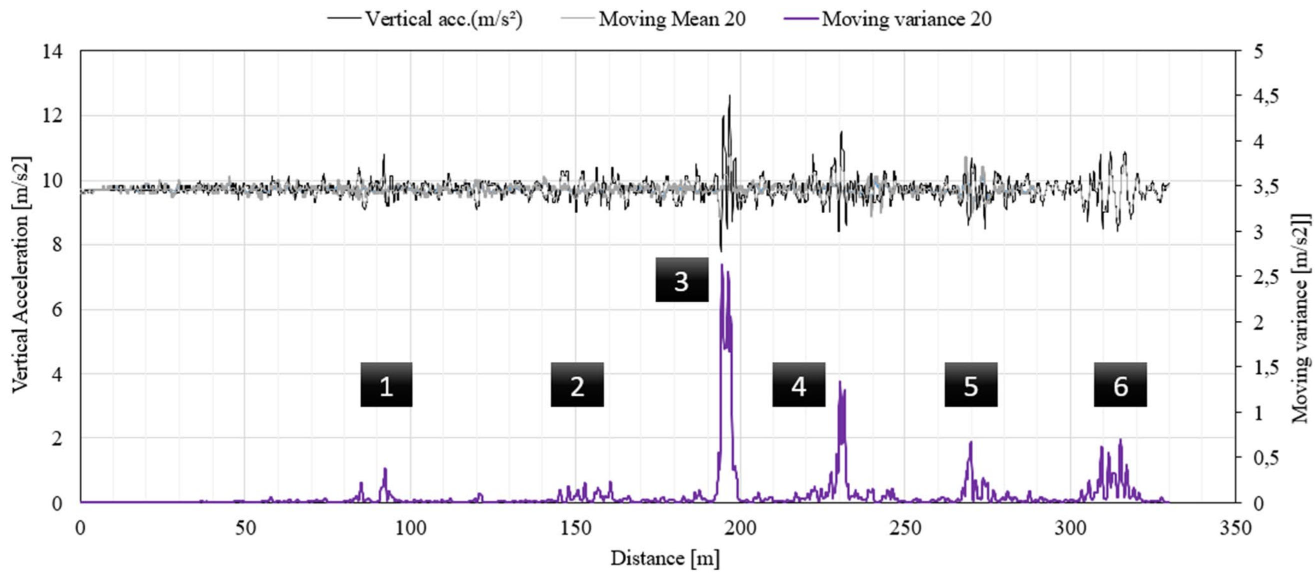


Fig. 13 Via Olinto Nesi

Table 5 Local distress index results

Peak ID	Peak value of VAR20 [m/s^2]										LPB [m/s^2]	St. Dev [m/s^2]	Severity levels
1	0.383	0.432	0.394	0.339	0.383	0.382	0.414	0.340	0.408	0.369	0.385	0.0298	Moderate
2	0.207	0.226	0.203	0.222	0.230	0.215	0.240	0.240	0.250	0.240	0.228	0.0155	Moderate
3	2.812	2.679	2.432	2.687	2.638	2.548	2.727	2.524	2.717	2.622	2.639	0.1117	High
4	1.447	1.266	1.381	1.319	1.449	1.265	1.270	1.377	1.324	1.249	1.335	0.0754	High
5	0.668	0.660	0.736	0.708	0.741	0.633	0.643	0.685	0.691	0709	0.688	0.0370	Moderate
6	0.653	0.739	0.749	0.748	0.648	0.660	0.718	0.721	0.749	0.670	0.706	0.0428	Moderate

The road segment within via Olinto Nesi was selected to evaluate the effect on the vertical acceleration due to the vibration caused by damaged road surface characterized by the presence of multiple distress with different severity levels such as potholes, patches and cracking. The analysed VAR20 allows investigating the road pavement condition both in terms of local anomalies and of global segment damage.

4.3.1 Local pave box index

Six different local anomalies were highlighted in the 330 m long road segment within via Nesi. Peaks were characterized by the VAR20 values summarized in Table 5. Four LPB indices had moderate severity and two of them were instead classified in high severity.

The first 50 m of the street was characterized by a moving variance very close to 0 that indicates a good road surface condition. Instead, the remaining road segment was characterized by the presence of numerous peaks at different intensities. Peaks detected vary between the three different levels of severity to indicate a poor condition of road pavement. While the six "major peaks" were detected in all passages the others detections did not occur in all surveys carried out.

To demonstrate the effectiveness of the proposal, a visual survey was carried out as for the other road segments. The six peaks characterized by moderate and high severity were immediately identified. In Fig. 14 these distresses and their severity levels were represented.

The mean value of the peaks located within via Nesi ranges from a minimum of 0.228 m/s^2 to a maximum of 2.639 m/s^2 (anomaly n.3—Fig. 14). The comparison between the visual survey and the proposed automatic detection confirms the robustness of the method to detect the distress characterized by a moderate oh high level of severity. All the passages allow the identification of these anomalies.

The "minor peaks" (0.05 m/s^2—0.1 m/s^2) were widespread in this section characterized by strong irregularity of the entire road surface (excluded the first 50 m). As suggested by the Eriksson and Mednis researches [28, 37] only the vertical acceleration contained in more than four findings was taken into account for post-processing and

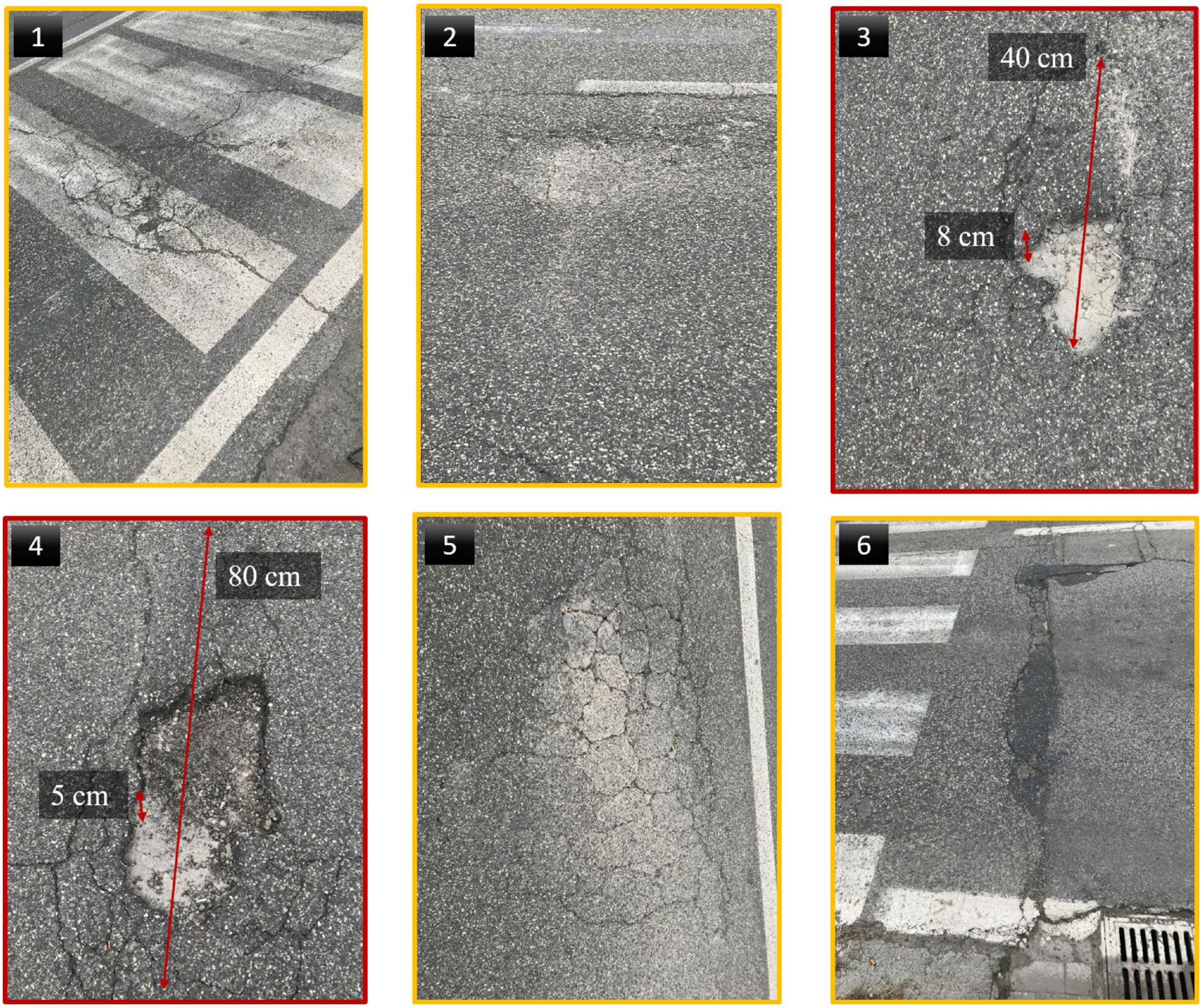


Fig. 14 Anomalies located in via Olinto Nesi

Table 6 Global distress index results

Segment ID	Segment length[a] [m]	a_v mean value [m/s^2]	VAR20 mean value [m/s^2]	GPB	Severity levels
1	100	9.7205	0.0179	0.2276	Good
2	100	9.7261	0.1153	1.4354	Poor
3	100	9.6995	0.0862	1.0727	Poor
4	30	9.6613	0.1325	0.1480	Good

[a]All the values in the table have been referred to the segment' length

LPB index evaluation. The other information was considered as accelerations' noise (false positive).

Due to the severe distresses in the road surface the proposed monitoring procedure allowed to identify about 90% of the anomalies corresponding to the peaks. Only two minor distresses (10%) were not detected. Some vibrations, of the measured signal, were not related to any visible anomalies.

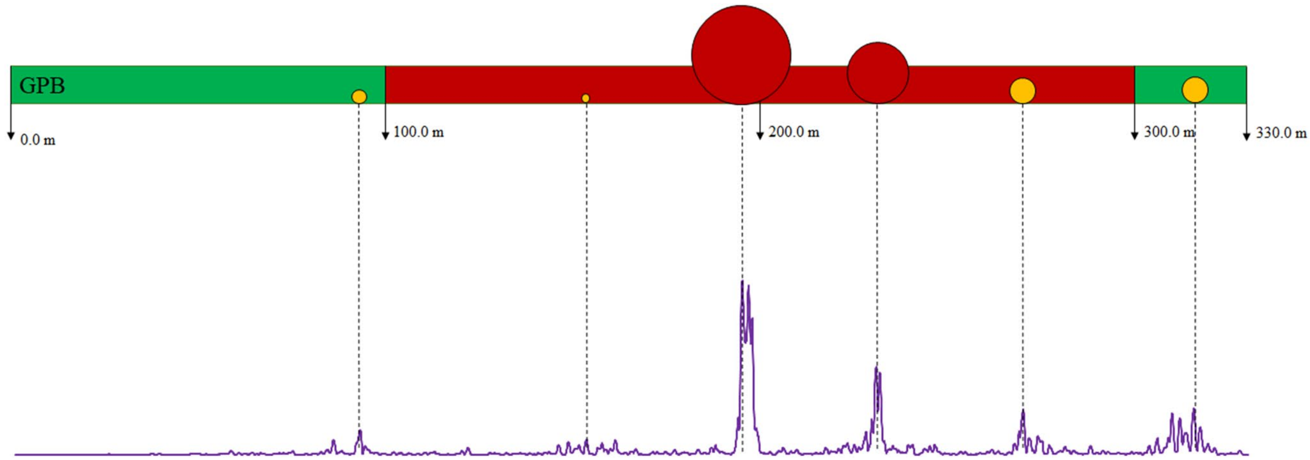


Fig. 15 Graphically results—via Nesi

4.3.2 Global pave box index

Table 6 summarized the result obtained in the evaluation of the global distress indices on via Olinto Nesi.

The GPB index represents the average value of the ten surveys conducted. The GPB values shown in Table 2 for the homogeneous sections n.1 and 4 described a good global condition of the pavement analysed. The values of the global index for both section n.2 and n.3 were instead greater than 0.76; therefore, the homogeneous segment will be classified in poor condition. These findings were consistent with the trend of the moving variance curve in Fig. 13.

According to the manual verification conducted to demonstrate the robustness of the monitoring process, the measurement carried out allowed a good description of the via Nesi road surface. In conclusion, the comparison of the numerical values of the estimated integral (GPB index), for normalized sections over 100 m, with the visual survey carried out on the road pavement, allowed to verify the consistence of the proposed monitoring process with reference to a road section characterized by poor surface conditions. The results obtained in the via Nesi analysis confirms the aptitude of the proposed monitoring methodology to fully detect the relevant anomalies on the road surface.

It should be emphasized that by combining the two indices, the methodology was able to describe the road pavement condition with good reliability, leaving out only small percentages of anomalies characterized by low severity.

4.4 Graphical results

The proposed procedure provides RAs with two different information on road pavement conditions; the first referred to the presence of local distresses (potholes, patches and cracking) with different severity levels and the second one referred instead to the global status of the road pavement condition.

It can often happen that some relevant, but local, distresses were located within the homogeneous section, but the overall segment (100 m long) was characterized by a good regularity. Therefore, the presence of the single distress does not highlight the need to urgently restore the road surface of the entire lane evaluated, but only on a small area, such as a pothole.

However, in this condition is very important to graphically represent the findings with the aim of offering RAs the possibility to understand how anomalies spread on the road surface and where they can constitute a danger and/or

Fig. 16 GIS maps

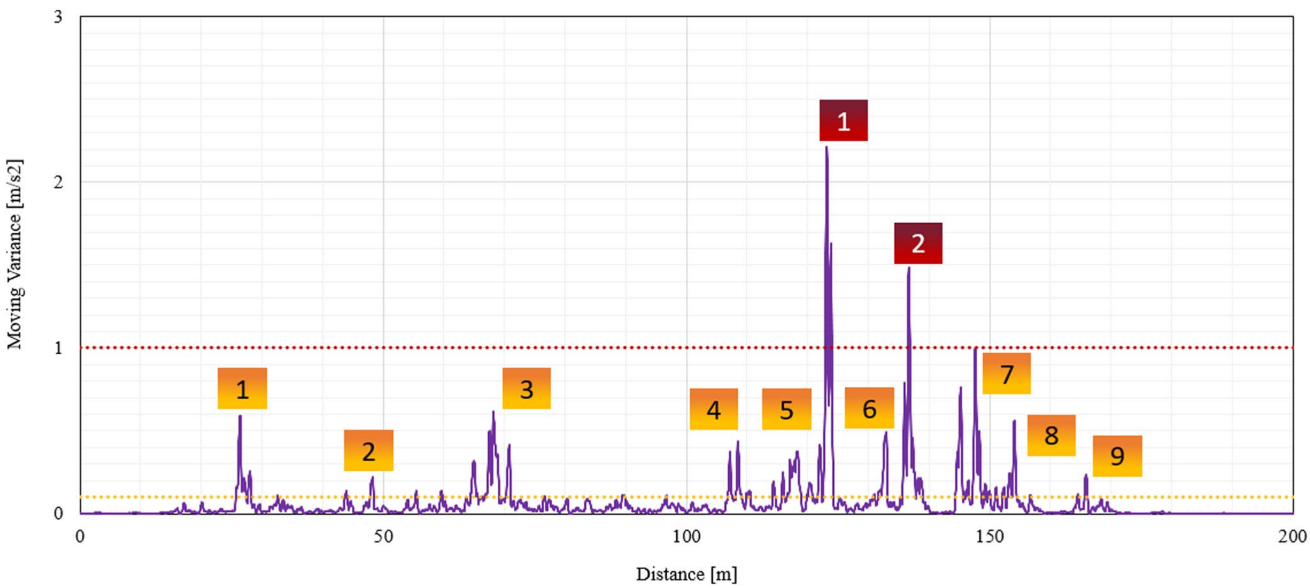


Fig. 17 Via Toscana—moving variance and peaks individuation

generalized traffic safety problem, especially for the two-wheels drivers. In Fig. 15 is shown the graphically methodology proposed for the representation of the road distress on the GIS map (Fig. 16). While the entire homogeneous section is coloured green (or yellow or red), as a function of the global severity level, it is necessary to insert information relating to the local distresses on the map, through an attribute (e.g. circle) of different colour and size based on the LPB index.

As highlighted in Sect. 4.1, when the GPS connection cannot be maintained, even good localization accuracy cannot be achieved. However, in this process, one error in GPS position less than 5 m does not represent an important factor, because the main objective of the research is represented by the screening of the road pavement condition of the entire road network. To identify the most damaged road pavement sections (about 100 m or longer) the procedure needs a large number of recorded measures. In this context is not important to know the exact position of the "distress" because each single anomaly and its severity were estimated with a function independent of the GPS position. However, the error in GPS position can affect only the local index because the global index will still be related with a section length not less than 100 m, where the error in position have to considered be negligible.

5 Via Toscana

As previously described, via Toscana is 200 m long and has, therefore, been divided into two 100-m-long homogeneous segments. All tests were conducted with the previously used Seat Leon. Also in this case, according to the posted speed limit in the area, all tests were conducted with speed around 40 km/h.

In Fig. 17, the moving variance graph referred to the monitoring on via Toscana is represented. It can be observed that two peaks were characterized by high severity level, while nine different peaks were characterized by moderate severity levels. There were numerous peaks that fell within the minimum severity level (0.05 m/s^2 – 0.1 m/s^2).

In Table 7, both the local and global distress indices are summarized. The monitoring campaign allowed to characterize both the segment referred to the analysed lane in serious distress condition. In the segment *n*.1, three moderate peaks were identified. In the segment *n*.2, six moderate peaks and two high peaks were detected.

Table 7 LPB and GPB indices' results

Segment ID	Peak ID	LPB	Severity levels	GPB	Severity levels
1	1	0.5936	Fair	1.08	Poor
	2	0.2237	Fair		
	3	0.6206	Fair		
2	4	0.4350	Fair	2.17	Need to repair
	5	0.3784	Fair		
	1	2.2147	Poor		
	6	0.9991	Fair		
	2	1.4836	Poor		
	7	0.9991	Fair		
	8	0.5599	Fair		
	9	0.2364	Fair		

Fig. 18 Images of the segment $n.1$ and 2, respectively, on left and right

Fig. 19 Graphical results of the monitoring process—via Toscana

In Fig. 18, two views of the road pavement condition are shown. The figure on the left refers to the first homogeneous segment (0–100 m), the other one (100–200 m) refers to the second segment characterized by a very damaged road surface. The two images are consistent with the result obtained in terms of LPB and GPB and allowed to observe both local and widespread distress, such as cracking.

In Fig. 19, the result obtained for the road section, corresponding to the GIS display of the RAs, is shown.

The findings of the analysis of the three streets, selected to optimize the methodology have highlighted that, with good reliability, all "severe distress" were detected and classified. It is probable that 20–30% of minor anomalies were not detected. However, the global road pavement condition described did not change the overall assessment given and the need to urgently repair the street.

The results obtained are representative of a single passage. They were characterized by a low time consuming. In a few minutes, it was possible to characterize the road pavement condition with a quality comparable to that obtained from a PCI survey, which instead requires numerous hours of monitoring, personnel exposed to traffic, and a lot of post-processing time [54].

Despite the goodness of the first results obtained, it is very important to highlight some different aspects of the process adopted which are still being tested. There are many variables that affect the monitoring procedure's results. These can be divided in two categories; the first are correlated with all the parameters that charaterize the car configuration, such as tire pressure and vehicle types (sedan, SUV, microcar, etc.); the second one, instead, is correlated to the "standard of the test condition", such as the different positions of the black boxes inside the vehicle, speed of the surveys and different trajectory inside the same lane analysed. All of these parameters could conduct at different results, which are being analysed one by one.

In this research, the first investigation on the effect of car type on results was defined. Statistical analysis conducted shows that the maximum ranging from the local and global indices is not greater than the 1.5% and 0.5%, respectively, with very different type of cars (sedan—Seat Leon VS SUV—Dacia Duster). Obviously an increase in the local/global index corresponds to a decrease in the difference in the result obtained for different vehicles. More accurate researches are on-going, therefore specific data are not reported in this paper.

6 Conclusions and future developments

The importance of the road condition represents an ordinary challenge for the RAs. The bad condition of road pavement causes discomfort, damage vehicles and unsafety for all road users. Because RA budgets are generally constrained, determining where roads need repair and maintenance becomes very important. An efficient monitoring of the road surface condition, therefore, allows RAs to optimize their limited resources.

Nowadays, different monitoring methodologies are available; some of them are characterized by high performance and high costs, others instead, are characterized by limited performance and high time consumption. The proposed distress-detection algorithm was designed and implemented to satisfy the needs of RAs, using a data collection based on the mobility of the vehicles that gather data from their movement through the road network.

The system proposed, called *Pave Box*, consist in inertial device (black box) fixed inside the vehicle that measures the vertical acceleration and GPS position of the car, detecting and reporting the road pavement condition on the database. The proposed methodology is based on simple algorithms that process the database and give RAs the position and severity of the anomalies present on the road surface.

The findings described in this paper demonstrate that the *Pave Box* procedure allows detecting different types of road surface distress, such as potholes, patches and cracking. The proposed algorithms allow to process the vertical acceleration measured by black boxes inside the vehicle and define two different road surface condition indices; the first, named LPB, referred to the presence on the road surface of local anomalies and the other one, named GPB, to evaluate the global distress level of the entire of the 100-m-long section. The approach aims to quickly solve the most important need of the RAs: screen and know the real condition of their damaged network.

The robustness of the process is shown, to correctly detect the presence/absence of the anomalies on the road pavement and their severities. Therefore, the tool does not aim to punctually analyse all situations that can introduce only a discomfort for the motorized road users, but first "to alarm" the RAs to intervene and restore the most dangerous situations because the distress severity is high.

The reliability reached (in term of the global evaluation) is comparable with the one obtained in the traditional PCI surveys, but with low cost and time saving. The PCI visual survey was selected to set the provided process on the basis on approved, spread, valid and reliable monitoring procedure across the word, despite the literature provide different indices in describing the road pavement surface, such as IRI, which in urban areas can be poorly correlated to user comfort.

The comparison between the results with the traditional visual survey carried out on the same road section allows to verify the consistence of the proposed monitoring process also with reference to road sections characterized by a good surface conditions. The sample selected sections, characterized by different pavement condition severity levels, show that the *Pave Box* system detects all severe (moderate and high levels) anomalies. In addition, the system is able to detect about the 70% of minor distresses. Only 20–25% of false positive were revealed.

The good results obtained in this first part of the research promoted the development and evaluation of a tool that merge the importance of quickly detect the dangerous distresses in the road pavement, with the detection of all minor anomalies that could affect the users' comfort describing the overall ride quality offered by the road surface by means of the PSR index. With this improvement the percentage of false positive will decrease, and a complete monitoring process could be offered in to optimize the decision-making process to efficiently maintain the road network.

A big improvement in the methodology could be reached exploiting all the data collected by all the vehicle equipped by black boxes (such as taxis, medical auto, police cars and finally also private cars) allowing to screen the entire road network using data recorded opportunistically from ordinary transit on the road network, allowing finally to exploit a "big data" to offer in "real time" an ever increasing reliability of the pavement condition surveys.

The construction of an organized database or cloud will allow the storage, process and analysis of all data recorded by the vehicles on the road, so that each information could be transformed into knowledge about the road pavement condition. With an increasing trend, data are continuously collected and updated through new information, to performing real-time analysis and to make automatic the responses based on big data, addressing issues faster than human response time to screen and "self-improve" its responses' accuracy.

There are a lot of variable that can affect the reliability of the results given from the final system. Its architecture need to consider all the variable named in this paper, thus some experimentation is currently underway with the aim of analysing the effect of the most important variables, so that they can be implemented into the decision algorithm.

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